

The Effect of Shared Information on Pilot/Controller Situation Awareness and Re-Route Negotiation

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Abstract--The effect of shared information is assessed in terms of pilot/controller negotiation and shared situation awareness. Pilot goals and situation awareness requirements are developed and compared against those of air traffic controllers to identify areas of common and competing interest. A part-task simulator experiment is described which probes pilot/controller interaction in areas where common information has the potential to lead to contention, as identified in the comparative analysis. Preliminary results are presented which suggest that shared information can effect more collaborative interaction between pilots and air traffic controllers.

I. INTRODUCTION

The technology to deliver digital datalink communication between aircraft and the ground is well developed. Current datalink applications include pre-departure clearance delivery via the Tower Data Link System, global voice and data communications via satellite (SATCOM), and weather uplinks via Terminal Weather Information for Pilots (TWIP). The FAA's proposed future National Airspace System (NAS) Architecture (Version 3.0 draft) calls for an expansion of these existing services to support a Controller-Pilot Data Link Communication (CPDLC) system. This system is expected to be integrated with parallel datalink efforts such as Automatic Dependent Surveillance broadcasts (ADS-B) and Aviation Weather Information (AWIN) systems.

Such advances will allow information which is not uniformly accessible today to be passively shared between pilots, controllers and other users. This sharing of information—a digital information "party line"—is expected to offer several benefits:

1. Improved shared situation awareness between agents;
2. The ability to better anticipate the needs and/or preferences of other agents;
3. A common informational context upon which to negotiate.

These benefits ultimately are expected to result in more cooperative interaction between agents, moving airspace operations closer to the envisioned goal of Collaborative Decision Making (CDM).

However, the sharing of information may effect a less desirable outcome, one characterized by increased voice communications, increased workload, and increased contention between agents. Midkiff & Hansman (1992) found that pilots were more willing to comply with air traffic control (ATC) when they knew their own information was inferior to that of ATC. Conversely, they found that pilots were more assertive and willing to question ATC when they knew their own information was equal or superior to that of ATC.

The implementation of digital datalink stands to alter the current "balance of information" between ATC and the flight deck. Today, flight crews typically have information superiority with respect to weather, while air traffic control typically has information superiority with respect to traffic. Datalink applications for weather and traffic information may serve to redress these imbalances by sharing this information between both parties. To the extent that a datalink system is successful in eliminating areas of information inferiority, the results of Midkiff and Hansman suggest that in some situations the availability of common information via datalink may result in increased negotiation, and with it commensurate increases in frequency congestion and workload. In short, it suggests the potential for less collaborative, less efficient operations. This paper summarizes the results of an exploratory, simulator-based experiment designed to probe this issue.

II. APPROACH

The evaluation of advanced cockpit- and ground-based automation systems such as digital datalink requires careful consideration of their effect on overall system performance with the human users in the loop. This study adopted an integrated human-centered systems approach, whereby the users were considered as functional components of the

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closed-loop system (Hansman, *et al.*, 1997). The study comprised three serial efforts:

1. Determine the goal structures and situation awareness (SA) information requirements of the users.
2. Compare the users' goal hierarchies and information requirements to identify areas of common, disparate or competing interest.
3. Based on the findings, design and perform simulator-based test scenarios which explore users' interaction and behaviors in environments where common information may serve competing goals.

III. DEVELOPMENT OF PILOT AND CONTROLLER GOAL HIERARCHIES AND SA INFORMATION REQUIREMENTS

In order to understand the effect of shared information in the system and how pilots and controllers might act on that information, it was necessary first to identify their roles, their motives and their informational needs. A comprehensive goal-directed task analysis was performed for commercial airline pilots (Endsley, *et al.*, 1998) to complement an existing analysis for en route ATC specialists (Endsley & Rodgers, 1994). Based on extensive focused interviews with subject matter experts, each task analysis constructed a comprehensive goal hierarchy from which the specific situation awareness information requirements were derived (see Figures 1a & 1b).

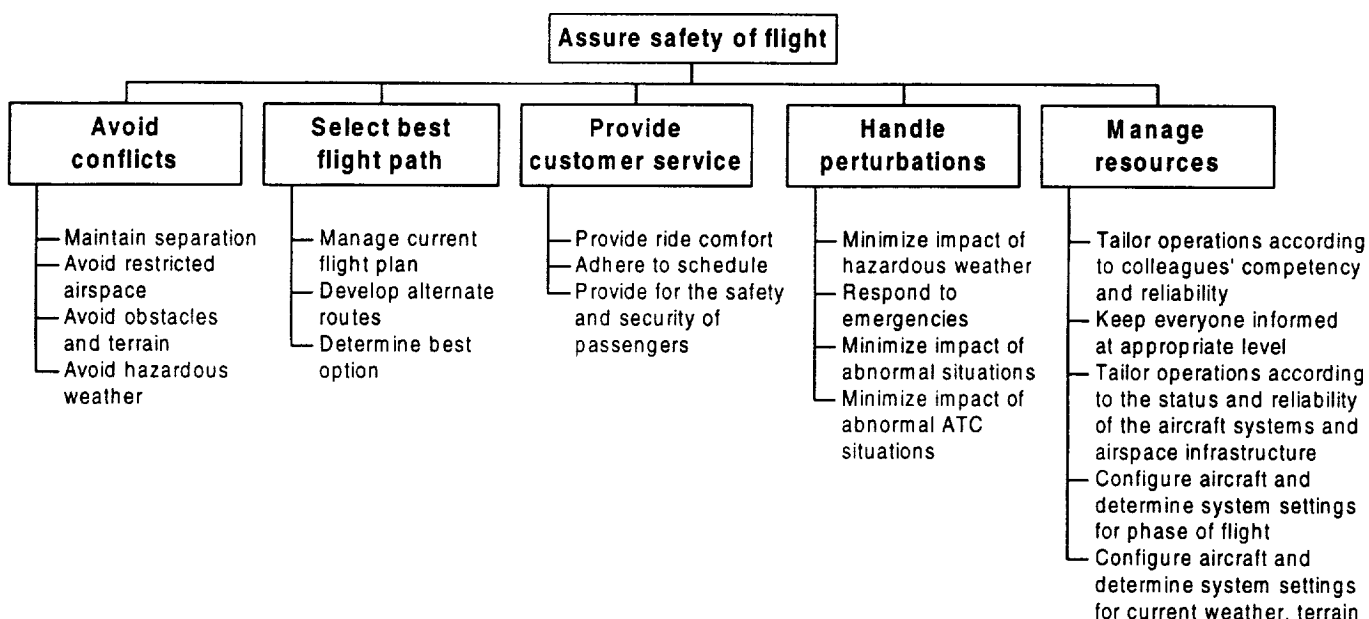


Figure 1a. Commercial Airline Pilot Top-Level Goal Hierarchy

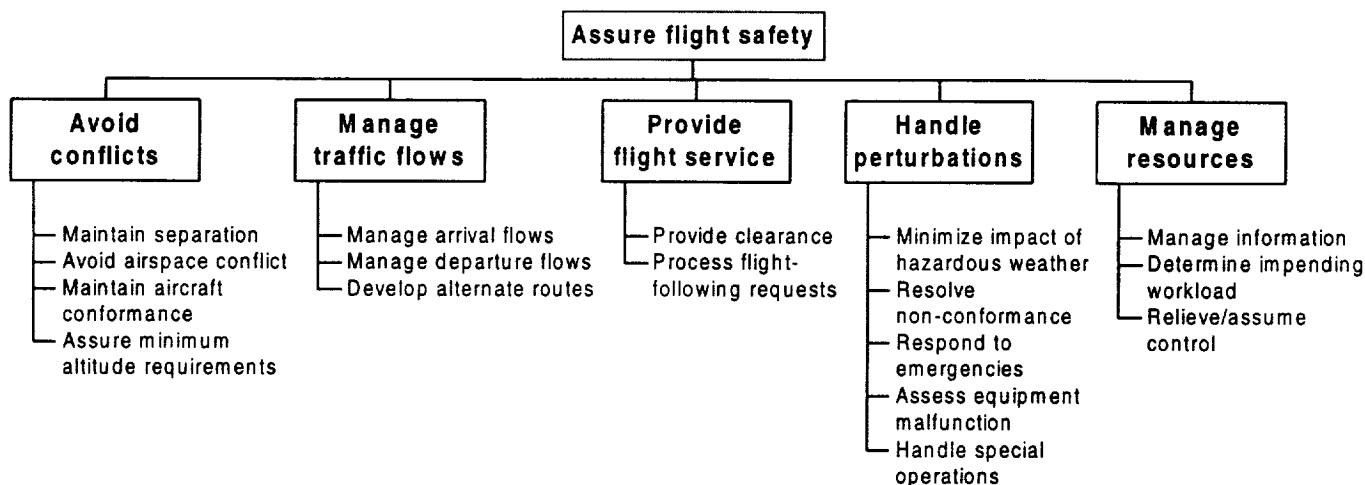


Figure 1b. En Route Air Traffic Controller Top-Level Goal Hierarchy

IV. COMPARISON OF PILOT AND CONTROLLER GOAL HIERARCHIES AND SA INFORMATION REQUIREMENTS

The individual pilot and controller task analyses were compared against one another in order to identify areas of common or competing interest between pilots and controllers. Figures 1a and 1b depict the high-level goals of pilots and controllers, respectively. At these higher levels, the goal structures are highly parallel, and there is considerable overlap between the two. Common goals include:

- Assure flight safety
- Avoid conflicts (e.g., aircraft, terrain, restricted airspace)
- Provide customer service
- Handle perturbations (e.g., weather, emergencies)
- Manage resources (e.g., people, systems)

The high-level goal comparison revealed the far-reaching effects of re-route decisions. All of the first- and second-level goals for both pilots and controllers are influenced by the current and future flight path. This suggests that re-route negotiations have broad and significant ramifications for both pilots and controllers and that each should have a vested interest in the outcome.

Comparison of the lower-level goals revealed that pilots and controllers often have competing interests with respect to re-route decisions. For example, pilots assess route amendments in terms of time or fuel efficiency, whereas controllers assess them in terms of their effect on separation and traffic flows. More generally, pilots' aircraft-centered goals often conflict with controllers' system-centered goals, creating the potential for less collaborative negotiations.

The information upon which such negotiations are conducted varies, but pilots and controllers reported that traffic and weather information often provide the impetus to change path and typically impose constraints on the available alternatives.

V. SIMULATOR-BASED EXPERIMENT

Based on the results of the task analysis comparison, an exploratory experiment was conducted to evaluate the extent to which shared information (via air-ground data link) may lead pilots and controllers to cooperate or compete when negotiating route amendments. To explore these issues effectively, the study required a live, realistic and challenging environment in which for pilots and controllers to interact. A part-task simulator experiment was developed in which two subjects—one pilot and one controller—would interact to handle common en route tactical situations in real time. Scenarios were designed to provide enough structure to challenge the subjects, but also with enough latitude to allow the subjects to interact freely and develop their own options according to their goals and priorities.

Given pilots' and controllers' mutual interest in the flight path and the different criteria by which they evaluate flight plan deviations, the experiment was directed at re-routing situations. The identified importance of traffic and weather information in re-routing situations was reflected in the experiment's use of traffic and weather elements in the test scenarios and the availability of a traffic and weather datalink as the independent variable.

Test scenarios were designed to represent common en route air traffic situations involving convective weather and moderate- to high-density traffic flows. Weather and traffic hazards were scripted to pose routing conflicts to the subject pilot and controller pair. The intent was not to pose conflicts that were necessarily difficult for one or the other to resolve. Rather, the intent was to design conflicts which would play on the competing goals of the pilot and controller to offer each subject a fairly obvious—yet different—solution, thereby raising the need for re-route negotiation.

Scenarios were executed alternately with and without a digital datalink for the sharing of traffic and weather information between the pilot and controller. Comparisons were made both within and between subjects. Of particular interest were indications of each subject's recognition of the other's constraints, anticipation of the other's needs and preferences, willingness to comply/cooperate or persistence in pursuing one's own preferred solution.

A. Experimental Design

The experiment paired an air transport pilot subject with an en route air traffic controller subject in a real-time simulated air traffic environment under present-day air traffic control procedures. Test scenarios featured traffic and weather elements specifically designed to create testable responses, a performance-based means for measuring situation awareness (Pritchett, Hansman, & Johnson, 1996). Testable response scenarios incorporated a hazard element (e.g., an intruder aircraft, a weather cell) that required the subject to take action, provided s/he was aware of the situation. An appropriate action taken by the subject indicated situation awareness; inaction indicated a lack of situation awareness. Subjects interacted within the simulation environment to resolve the traffic and weather conflicts. The availability of shared traffic and weather displays (via datalink) was manipulated as the independent variable as shown in Table 1. Examples of the cockpit and controller displays are shown in Figures 2 and 3.

Table 1. Test Matrix

Configuration	Weather information	Traffic information
Baseline (i.e., no datalink)	Pilot only	Controller only
Datalink enabled	Shared	Shared

The datalink was disabled in the baseline configuration. With the datalink disabled, there was no sharing of information. Weather information, in the form of six-color NEXRAD reflectivity imagery, was available only to the subject pilot on the cockpit map display; the subject air traffic controller received no weather information. Conversely, traffic information—including aircraft position, call sign, track, altitude, and ground speed—was available only to the subject controller via the plan view display; the subject pilot received no traffic information. Information was partitioned in this way to establish clear information superiority for one party relative to the other. Thus, in the baseline configuration, the pilot was in a superior position with respect to weather information, and the controller was in a superior position with respect to traffic information. This represented the information balance in the system today.

In the "datalink enabled" configuration, weather and traffic information were shared between the pilot and controller. Figures 2 and 3 illustrate how the weather and traffic information was displayed to the pilot and controller. The baseline weather information available to the pilot via the cockpit map display was datalinked to ATC and displayed as an overlay on the controller's Plan View Display (PVD). Similarly, the baseline traffic information available to the controller via the plan view display was datalinked to the cockpit and displayed on a prototype Cockpit Display of Traffic Information (CDTI). The pilot's CDTI depicted the position, call sign, track, relative altitude, and relative

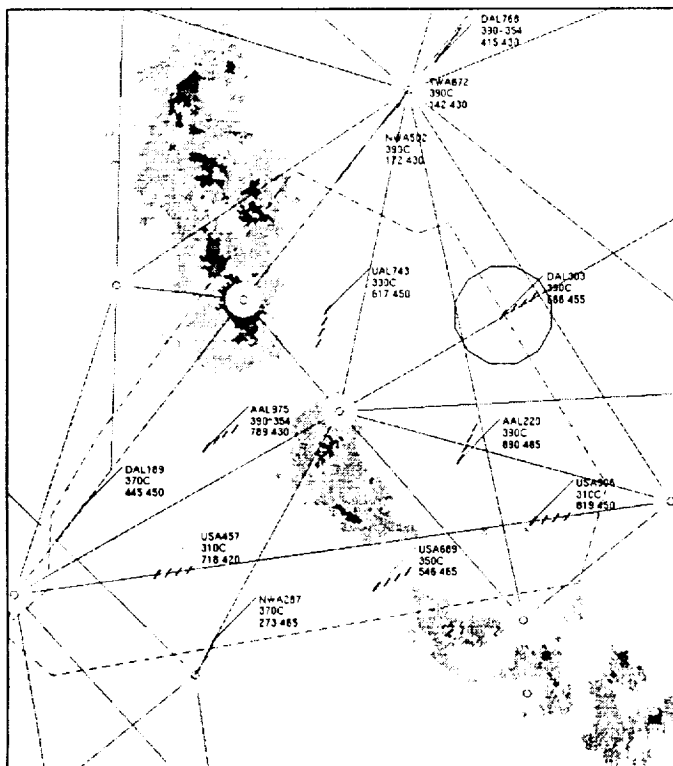


Figure 2. ATC Plan View Display in "datalink enabled" configuration. Note that the subject pilot's aircraft is DAL303, positioned inside the six-mile radius "J ring".

ground speed of all aircraft within 40 miles and 2600 feet in altitude.

Each pilot-controller subject pair performed three test scenarios two times, once with shared traffic and weather information (i.e., datalink enabled) and once without (i.e., baseline configuration). All scenarios took place in a high-altitude sector in Indianapolis Center airspace. Each scenario ran for approximately ten minutes and featured between 12 and 18 aircraft transitioning the sector in the presence of convective weather activity. Those aircraft not piloted by the subject pilot were controlled by a confederate pseudo-pilot, who also interacted with the subject controller and subject pilot via radio communication. Certain elements of each repeated scenario were changed (e.g., aircraft call signs, trajectories of non-factor traffic, etc.) in order to disguise the second iteration.

Pilot and controller situation awareness was measured using the testable response method. Radio communications were recorded and coded using a methodology adapted from Foushee, Lauber, Baetge, & Acomb (1986). Workload measurements were taken using the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). Subjective ratings regarding the value of the shared information were also collected.

In order to observe pilot-controller interaction in a real-time, complex workload environment, MIT's distributed, interactive, multi-agent simulation facility was used

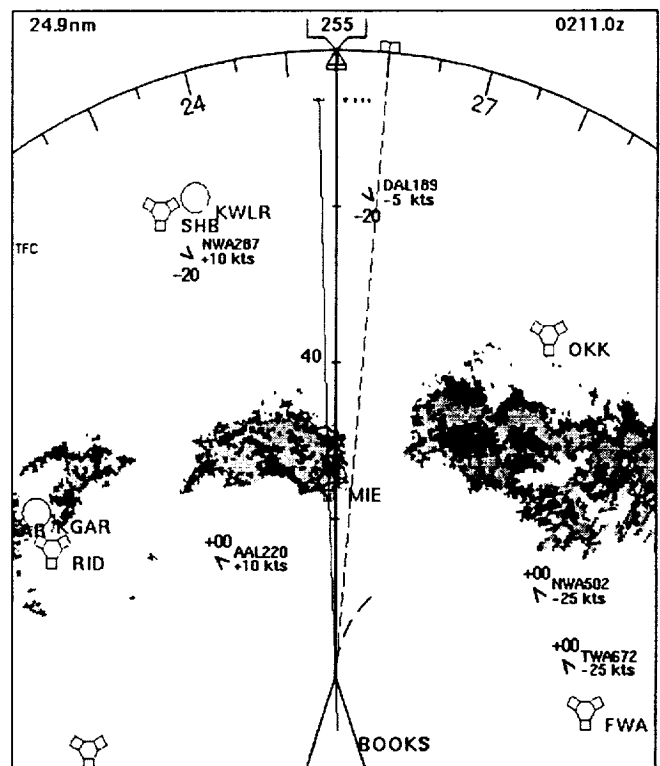


Figure 3. Cockpit map display in "datalink enabled" configuration, as seen by the subject pilot of DAL303.

(Amonlirdviman, *et al.*, 1998). The facility was configured to network one part-task advanced cockpit simulator, one part-task en route ATC workstation, one multi-aircraft pseudo-pilot station, and live voice communications between them, creating a real-time interactive air traffic environment.

B. Preliminary Results

Five pilot-controller teams have performed the experiment to date. All controller subjects were Full Performance Level (FPL) ATC Specialists with an average of 12 years of experience, currently working the radar position at an Air Route Traffic Control Center (ARTCC). All pilot subjects were jet transport pilots with an average of 9,340 hours.

To fully counterbalance the test matrix, the test protocol requires a total of six test subject pairs. Thus, caution is advised as the results presented here are subject to change with the addition of the remaining data. Furthermore, the test matrix is currently unbalanced, as three subject pairs performed the baseline configuration first while two subject pairs performed the "datalink enabled" configuration first.

1) Situation Awareness

Each test scenario included one weather-related testable response condition and one traffic-related testable response condition. Both the pilot and controller were monitored for their awareness of each testable response condition.

Figure 4 summarizes their situation awareness with respect to weather. Pilots, having the benefit of the weather display for all test scenarios, demonstrated awareness of all of the weather-related testable response conditions. Controllers, without the benefit of a weather display in the baseline

configuration, demonstrated awareness of only 40% of the weather-related testable response conditions. When provided a shared weather display, controllers demonstrated awareness of 93% of the weather-related testable response conditions. In some cases, the controllers gave conflicting indications of their awareness of the weather conditions. In such cases, the controller's testable response result was labeled "ambiguous".

Figure 5 summarizes pilot and controller situation awareness with respect to traffic. Pilots, without the benefit of a traffic display in the baseline configuration, did not demonstrate awareness of any of the traffic-related testable response conditions. In many cases, the controllers recognized the traffic conflict before it became a significant threat to the pilot and would either advise the pilot of the traffic or vector the pilot accordingly. In such cases, the pilot's testable response result was labeled "ambiguous".

Controllers, having the benefit of their plan view traffic display for all test scenarios, demonstrated a high level of awareness of the traffic-related testable response conditions. In some cases, controller-issued clearance amendments inadvertently resolved the traffic-related testable response condition before it arose; such cases were labeled "ambiguous" with respect to controller situation awareness.

These results indicate that controller SA with respect to weather improves with the addition of a weather overlay to their plan view display. Similarly, the results suggest that pilot SA with respect to traffic improves with the addition of a CDTI.

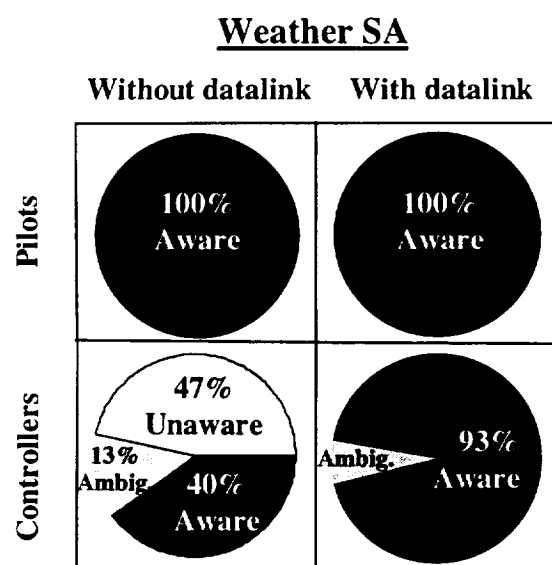


Figure 4. Pilot and controller awareness of weather-related testable response conditions.

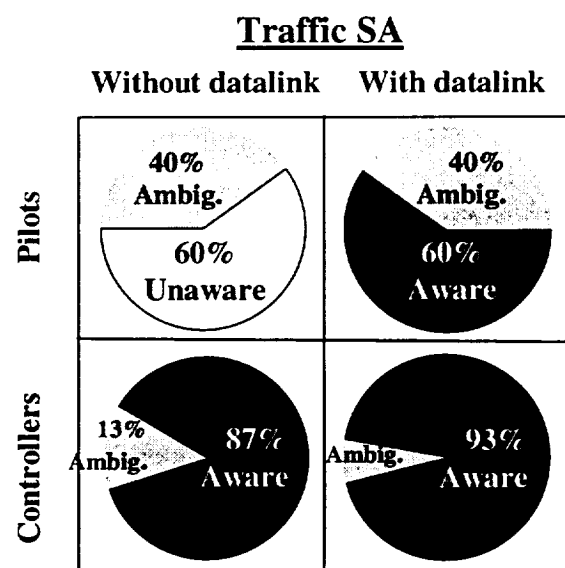


Figure 5. Pilot and controller awareness of traffic-related testable response conditions.

Pilot and controller workload was measured using NASA-TLX. In general, the availability of shared information did not affect the workload in any systemic way, either individually or in a team sense.

In the 30 test scenarios completed thus far, two operational errors¹ have been observed, both occurring in the baseline (i.e., non-datalinked) configuration. It is important to note that the test scenarios were challenging by design. Controllers were operating an air traffic sector other than their usual "home" sector and did not have the benefit of a conflict alert function or a D-side controller to assist them. However, the fact that both operational errors occurred in the non-datalinked environment does suggest that shared information may help the controller build and maintain situation awareness with regard to separation issues.

2) Communication and Negotiation

All radio communication was recorded, coded by category and topic, and analyzed. Figure 6 illustrates how the transactions conducted over the voice channel changed with the introduction of the datalink. As shown at the left, the number of transactions between the pilot and controller decreased slightly when the datalink was introduced. Despite this decrease, the number of transactions for negotiating re-route clearances increased, and the number of other transactions (including traffic advisories, ride

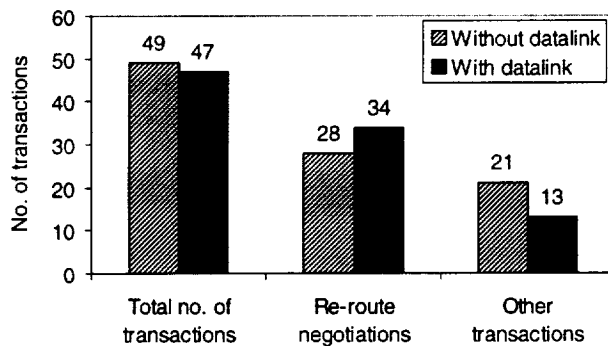


Figure 6. Voice communication transactions by topic

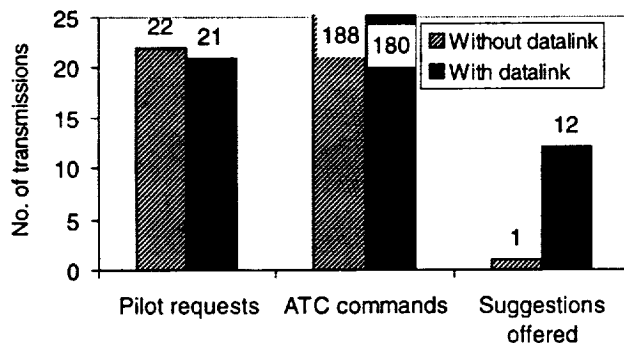


Figure 7. Voice transmissions by category

¹ An operational error is defined as lateral separation of less than five miles and vertical separation of less than 1000 feet.

reports, etc.) decreased. Although these results are not statistically significant, they suggest that the availability of shared traffic and weather information may induce increased negotiation of re-route clearances.

Figures 7 and 8 illustrate how the character of pilot-controller interaction changed when the datalink was introduced. Figure 7 shows that pilot requests and controller commands both dropped slightly, albeit not significantly. With the datalink enabled, the pilot and controller made more voluntary suggestions to one another for specific route amendments. This verbal exchange of re-routing ideas, options and preferences was rarely evident in the baseline configuration and is statistically significant at the 5% level ($p < 0.05$). Finally, Figure 8 illustrates that controllers were more proactive in providing weather advisories to pilots when they had the weather information overlay. This result is statistically significant at the 2% level ($p < 0.02$).

3) Subjective Responses

At the conclusion of each test session, subjects were asked to provide a subjective rating of the value of the shared information on a scale ranging from "very detrimental" to "neutral" to "very valuable". Figure 9 summarizes the responses of pilots and controllers separately. Pilot feedback was unanimously favorable, and all of the controllers rated the information as "very valuable".

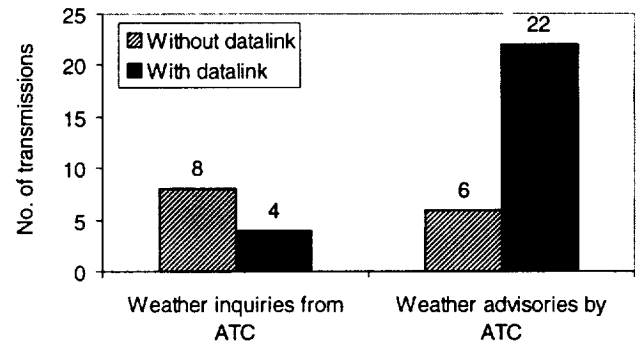


Figure 8. ATC voice transmissions regarding weather

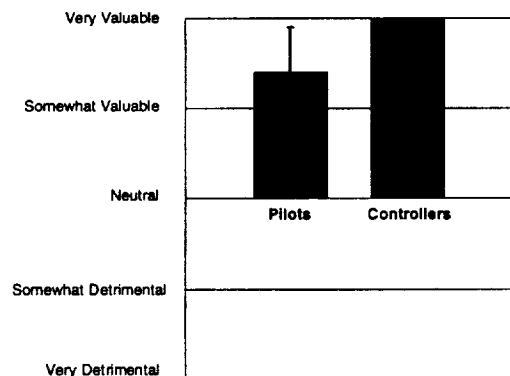


Figure 9. Subjective ratings of the value of the shared information

While controllers were enthusiastic in their support for the shared weather display, their opinions on sharing their traffic information with the cockpit were mixed. Some controllers suggested that it could be useful to controllers and pilots when sequencing aircraft in the terminal area. Others expressed concern that arming pilots with such information might make pilots "less complacent" with regard to their approved clearances or assigned vectors. During the course of this experiment, pilot-controller exchanges were observed that corroborate each of these opinions.

VI. CONCLUSIONS

The comparison of pilots' and controllers' goals and SA information requirements revealed many parallels at the higher levels. At the more detailed, lower levels, however, pilots' aircraft-centered goals were found often to conflict with controllers' system-centered goals. In either case, the aircraft's present and future flight path was identified as a key element in the goals of pilots and controllers.

The preliminary experimental results indicate that situation awareness was improved when information was shared between the cockpit and the ground. Pilots' traffic situation awareness improved when traffic information was displayed; controllers' weather situation awareness improved when weather information was displayed. Operational errors were reduced in the process.

Pilots and controllers also exhibited behavioral changes. When information was shared, there were fewer requests for information, and controllers provided more frequent weather advisories to pilots. Pilots and controllers were more likely to suggest preferred route amendment alternatives to their counterparts, and re-route negotiation increased in the process.

Based on these preliminary results, it appears that sharing information between flight crews and air traffic controllers is beneficial in terms of improved situation awareness and the behaviors it seems to foster. There is evidence that pilots and controllers, better able to recognize the constraints faced by their counterparts, are able to set aside their personal motives in re-routing situations and make an effort to meet the needs or preferences of their counterpart. One should bear in mind, however, that the test subjects for this study were self-selected volunteers, and therefore their negotiating demeanor may not necessarily be representative of the larger pilot and controller communities.

As with any interpersonal interaction, an individual subject's style, experience, and personality had an observable influence on the nature of the pilot-controller interaction. For example, whereas some controllers exhibited no change of strategy when information was shared, one (who had extensive military flying experience) became very proactive when provided with the shared information, assigning "preemptive" vectors around weather before the pilots could make re-route requests of

their own. In that case, the reallocation of the weather information appeared to effect a corresponding reallocation of authority for selecting route amendments around weather.

VII. ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration/Ames Research Center under grant NAG 2-716 and by TASC as part of the FAA Center of Excellence in Operations Research.

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